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Comparison of Protective Breathing Equipment Performance at Ground Level and 8,000 Feet Altitude using Parameters Prescribed by Portions of FAA Action Notice A-8150.2

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16. Abstract Two types of crewmember protective breathing equipment (PBE) were performance tested for compliance with Action Notice A-8150.2 at ground level (-1,300 feet) and 8,000 feet altitude. PBE #1 was a "hood with oral-nasal mask," which used potassium superoxide to remove carbon dioxide and produce its oxygen supply. PBE #2 was a "hood only," which contained lithium hydroxide to absorb carbon dioxide and compressed oxygen cylinders to supply breathable air. The parameters tested were PBE oxygen and carbon dioxide levels, temperature, and breathing resistance-pressure. Five units of each PBE type were subjected to testing; for within-PBE comparisons each type of unit was worn by the same human subjects at both altitudes. Relatively little difference in PBE performance was obtained at the different altitudes for both types of PBE. Oxygen partial pressures were somewhat reduced at the higher altitude for both types of PBE, carbon dioxide partial pressure was slightly greater at ground level for PBE #2, internal temperature was higher for PBE #2 than PBE #1, and exhalation pressure was greater at ground level than at 8,000 feet for PBE #1. The results indicate that both types of PBE performed adequately for the intended purpose at either altitude, but further testing would be necessary to certify PBE to meet additional requirements, such as use at altitudes above 8,000 feet.			
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COMPARISON OF PROTECTIVE BREATHING EQUIPMENT PERFORMANCE AT GROUND LEVEL AND 8,000 FEET ALTITUDE USING PARAMETERS PRESCRIBED BY PORTIONS OF FAA ACTION NOTICE A-8150.2

INTRODUCTION

Current FAA regulations specify a requirement for testing the performance of crewmember protective breathing equipment (PBE) at both ground level and at 8,000 feet altitude. However, many representatives of the oxygen equipment industry feel that this testing requirement is unnecessary, since a device that works at ground level should be just as effective at altitude. This argument is based on the theory that the reduction in ambient atmospheric pressure with increasing altitude actually leads to an increase in gaseous flow within the PBE, thereby enhancing oxygen concentration levels without increasing carbon dioxide levels.

The study reported here compared established PBE performance parameters (i.e., oxygen and carbon dioxide partial pressures, temperature, and inhalation/exhalation pressure) at ground level (-1,300 feet above sea level) and at 8,000 feet simulated altitude for two types of PBE currently certified by the FAA. Intra-device comparisons of these variable were made in the Civil Aeromedical Institute's (CAMI) altitude chamber.

METHOD

Subjects: Seven male subjects completed this study; three of these subjects participated in tests of both PBE's. This arrangement allowed five tests of each type of PBE at both ground level and 8,000 feet altitude. Table 1 (below) provides demographics for the subjects. PBE #1 was tested on subjects 1-5, and PBE #2 was tested on subjects 6-10. Note that the subjects who were tested using both PBE's are subjects 1,7; 2,6; and 3,8. Subjects #4 and #5 were tested on PBE #1 only, and #'s 9 and 10 on PBE #2 only.

Altitude: All tests were conducted in the CAMI altitude chamber in Oklahoma City, OK (the elevation here is about 1,300 feet above sea level), either at ground level or at 8,000 feet simulated altitude.

Apparatus: PBE #1: PBE #1 is a "hood with oral-nasal mask" type of PBE, which uses a chemically generated source of oxygen. The device works by using potassium superoxide to convert the wearer's exhaled water vapor and carbon dioxide to oxygen, after an initial burst of oxygen is generated by a chlorate candle when the PBE is first activated. The amount of oxygen flow is, therefore, not constant, rather it is dependent upon the quantity of water vapor and carbon dioxide supplied in the wearer's exhaled breath. The chemical generator is mounted externally on the lower posterior portion of the hood, and attached to effluently-oriented valves in the oral-nasal mask by soft plastic tubes to form a closed loop. The oral-nasal mask fits snugly over the wearer's mouth and nose, preventing exchange of gases at its exterior edges. Exhaled carbon

TABLE 1
PHYSICAL CHARACTERISTICS OF TEST SUBJECT POPULATION

Subject Number	Age (yrs)	Height (inches)	Weight (lbs)	Neck. cir. (in/mm)	FVC* (L)
1,7	34	70	150	14.0/355	5.58
2,6	35	68	148	15.2/387	5.50
3,8	25	72	163	15.0/382	5.84
4	34	69	160	13.1/332	5.63
5	24	70	165	15.6/396	5.49
9	28	71	172	14.5/369	5.48
10	25	75	172	14.5/368	6.73

*=Forced Vital Capacity

dioxide and water vapor exit the oral-nasal mask through the valves and travel to the generator, which then disperses the newly-formed oxygen into the hood. An inwardly-oriented one-way valve in the oral-nasal mask allows the oxygen to be inhaled from the hood. Except for the small quantity of air remaining in the dead space in the oral-nasal mask at each breath, the wearer is provided with air that is essentially free of water vapor and carbon dioxide.

PBE #2: PBE #2 is a "hood only" type of PBE, which utilizes two small cylinders of compressed oxygen placed alongside the lateral external edges of the hood to provide continuous oxygen flow within the hood. These cylinders also release oxygen directly into the hood for use by the wearer, but since there is no oral-nasal mask within the PBE, exhaled carbon dioxide and water vapor remain within the hood as well. While carbon dioxide absorption is provided by packets of lithium hydroxide attached to the lower inside lining of the hood, there is no mechanism for absorption of water vapor.

Both types of PBE are designed to supply oxygen for no less than 15 minutes at the workload prescribed by FAA Action Notice A-8150.2. To monitor this flow, gas samples from PBE #1 were taken from within both the oral-nasal mask and the hood. Gas samples taken from PBE #2 were gathered in the upper region of the facial area of the hood, as well as from an area adjacent to the subject's mouth and nose to approximate as closely as possible the sampling technique used for PBE #1. Oxygen and carbon dioxide levels were measured continuously by mass spectrometer.

Inhalation-exhalation pressures and temperature were monitored via a probe connected to a Stathem pressure transducer and a copper-constantan thermocouple, respectively, both of which were positioned to provide oral-nasal measurements, i.e., from within the oral-nasal mask for PBE #1 and from the mouth and nose area of PBE #2 close to where the internal hood atmosphere was being sampled. The outputs of the pressure transducers were amplified

and, along with the mass spectrometer outputs, were fed to a Compaq III portable microcomputer equipped with a Metrabyte DAS-16C analog-to-digital data acquisition board for conversion, storage, and subsequent analysis using Labtech Notebook software.

Procedure:

Procedures for the tests were conducted as prescribed in FAA Action Notice A-8150.2. Prior to testing, each subject was fully informed about the test procedures and research objectives, after which each executed informed consent. Each subject was then given a physical examination, which included an exercise stress test conducted at the workload prescribed by the Action Notice. On the day of the test, each subject received an additional medical screening as well as instructions regarding the proper donning and functioning of the relevant PBE. EKG electrodes were then applied for medical monitoring during the test, and the subject was then escorted to the altitude chamber.

After adjusting the bicycle ergometer seat to the correct height, the subject was seated and connected to the cardiac monitor by the EKG electrodes and blood pressure cuff. The chamber door was closed, and the chamber adjusted to the proper altitude. After assuring that all equipment was functioning properly, the PBE was donned and activated. Then, the subject was instructed to begin pedalling the ergometer at a rate of 50 rpm, at which time the experiment protocol began. Subjects then followed the workload profile prescribed in Action Notice A-8150.2, as follows:

00 to 05 minutes at 0.33 watts/lb body weight
05 to 07 minutes at 0.66 watts/lb body weight
07 to 12 minutes at 0.50 watts/lb body weight
12 to 14 minutes at 0.66 watts/lb body weight
14 to 15 minutes at 0.33 watts/lb body weight

To simulate the actions undertaken during an actual emergency situation, subjects moved their heads slowly from side to side during the seventh minute, moved their heads up and down during the tenth minute, and recited the English alphabet verbally during the 13th minute of the test. At the completion of the workload profile, the PBE was removed, the subject was examined to assure no problems existed. The altitude chamber was then returned to ground level, (if it had been at a simulated altitude of 8,000 feet), before opening the door and returning the subject to the staging area.

RESULTS

Testing commenced on February 6, 1989, and continued through February 15, 1989.

The results for each parameter tested at ground level and at 8,000 feet altitude are presented separately for each PBE type. The statistical significance of performance differences between ground

level and 8,000 feet simulated altitude were calculated using the two-tailed "t-test for correlated means."

Oxygen Concentrations: Although oxygen partial-pressure values are not actually specified in Action Notice A-8150.2, such values were measured inside both types of PBE as described above.

PBE #1

In both the hood and oral-nasal mask, absolute oxygen values within the hood tended to increase for all subjects as the 15-minute time period progressed. In addition, during each individual minute of the 15-minute protocol, ground level oxygen values in both the hood and the oral-nasal mask were significantly higher than those at 8,000 feet ($p < .01$). Mean oxygen concentrations for the 15-minute test period for both the hood and the oral-nasal mask are presented in figures 1 and 2.

PBE #2

Recall that the gas samples for PBE #2 were taken from two areas inside the hood, as there was no oral-nasal mask. As for PBE #1, oxygen pressures throughout the test period were significantly higher in both hood locations at ground level than at 8,000 feet altitude ($p < .01$), despite slightly decreased absolute partial pressures in the later minutes. Mean values for the hood and mouth-and-nose areas for PBE #2 are shown in figures 3 and 4.

Carbon Dioxide Concentrations: Performance requirement 2(a) of the Action Notice states: "The mean carbon dioxide levels at the mouth and nose shall not exceed 4% for the entire test period, although the concentration may increase to 5% for a period not exceeding two minutes."

PBE #1:

Carbon dioxide levels at both altitudes did not exceed the 4% level for either the hood or the oral-nasal mask for any subject using PBE #1. Difference scores between ground level and 8,000 feet altitude also indicated very little change in measured performance when comparing the two altitudes. Mean carbon dioxide levels at both altitudes for the hood are presented in figure 5. The greatest differences in carbon dioxide levels, although insignificant, were recorded during minute 13 in the oral-nasal mask at ground level, when subjects were reciting the alphabet ($p < .09$; figure 6). Note that 4% carbon dioxide at ground level (-1,300 feet) = 29 mm Hg, and 4% at 8,000 feet = 22.6 mm Hg.

PBE #2:

Unlike PBE #1, the mean PBE #2 carbon dioxide levels, from both the hood and mouth-and-nose areas, tended to be higher at ground level than at altitude (figures 7 and 8). This effect was expected because of the exhalation of carbon dioxide back into the PBE.

HOOD O₂ VALUES

PBE # 1
GROUND LEVEL VS 8000 FEET

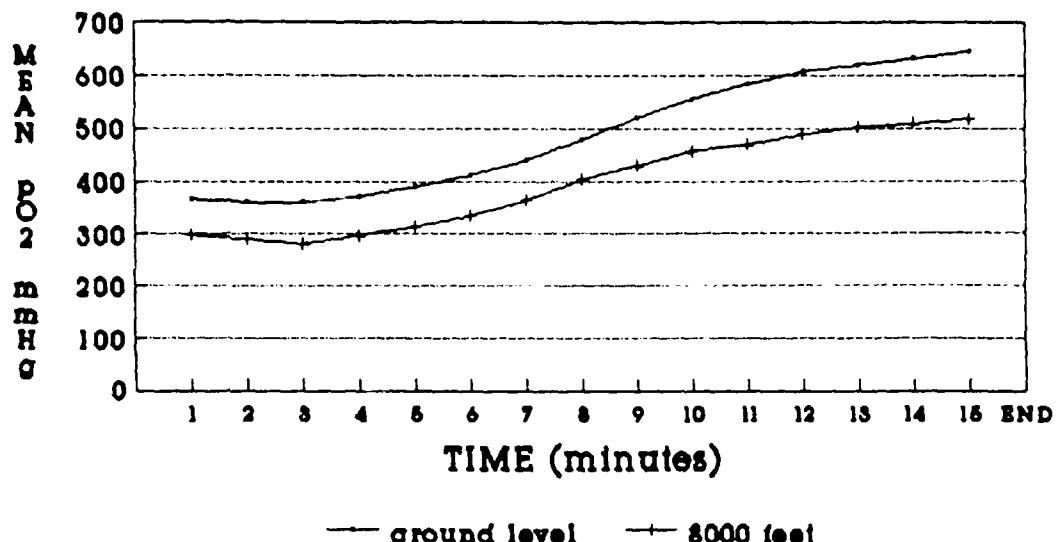


FIGURE 1

ORAL-NASAL O₂ VALUES

PBE # 1
GROUND LEVEL VS 8000 FEET

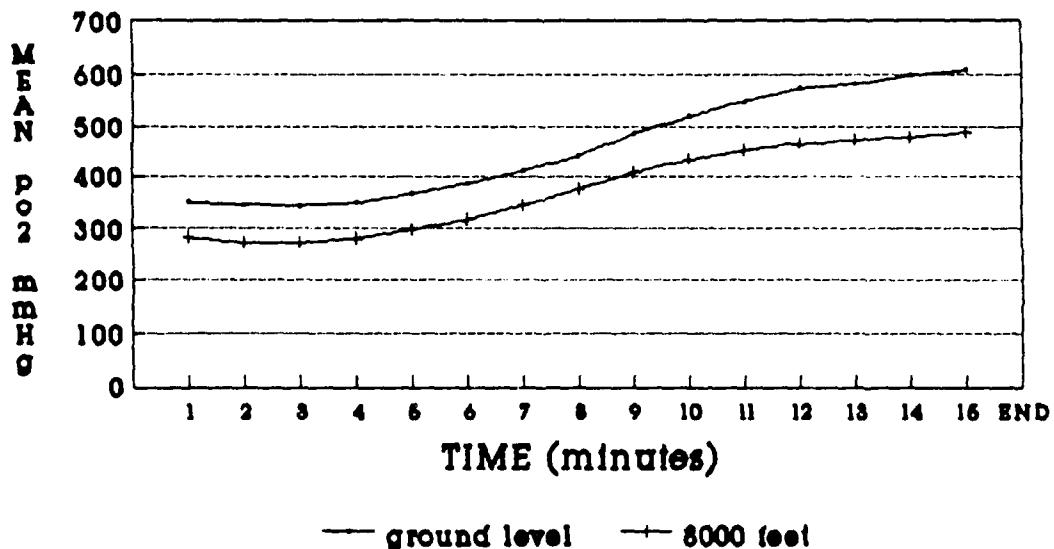


FIGURE 2

HOOD O₂ VALUES

PBE # 2
GROUND LEVEL VS 8000 FEET

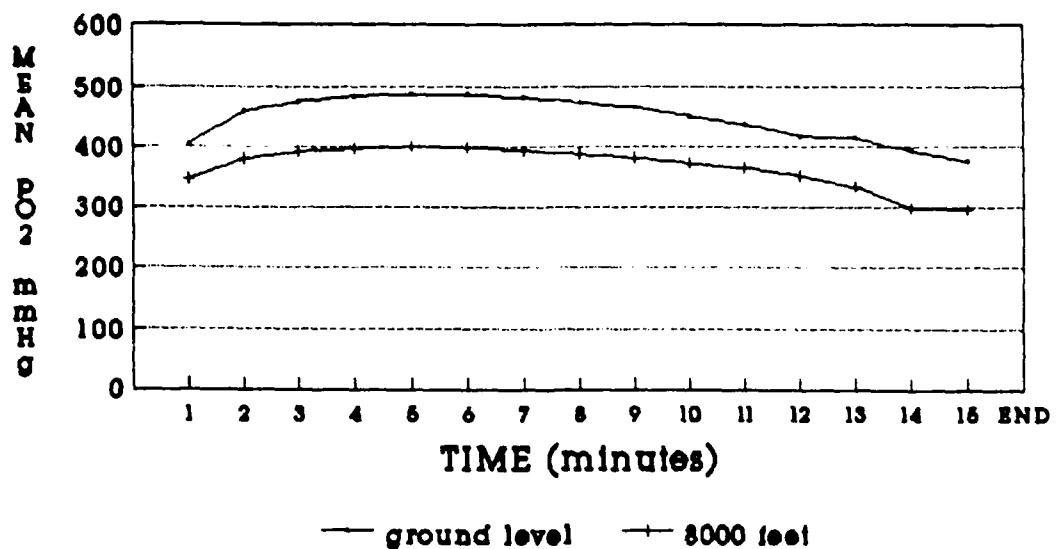


FIGURE 3

MOUTH-NOSE O₂ VALUES

PBE # 2
GROUND LEVEL VS 8000 FEET

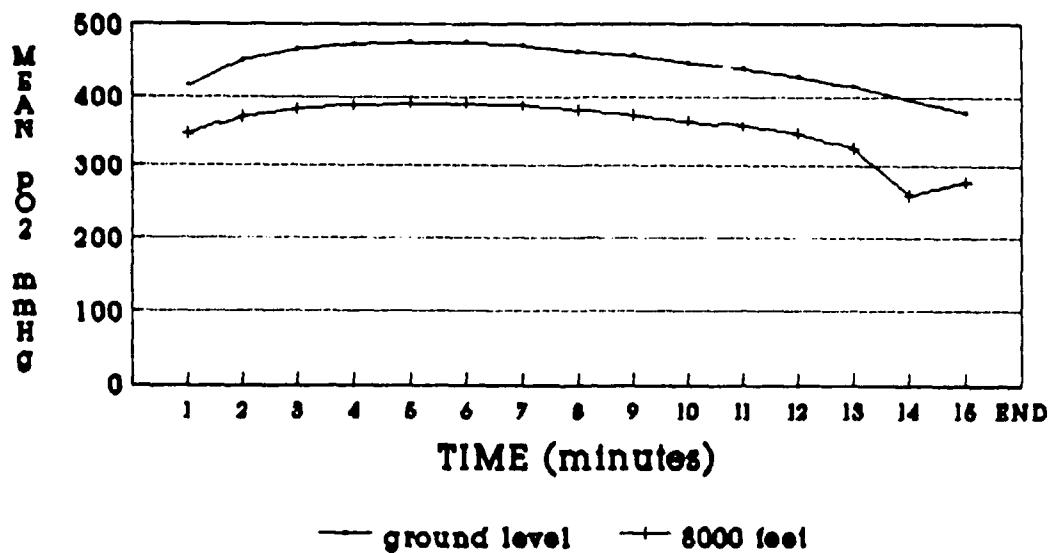


FIGURE 4

However, despite these mean differences, most minute-by-minute differences were insignificant. This divergence of effect occurred because changes in carbon dioxide levels for two subjects were opposite to the changes produced by the other three subjects during certain time periods. Except for the differences in fitness levels of the subjects, there is no obvious reason these profiles are so different or which of the profiles is most valid in determining the typical PBE function profile. Thus, for hood carbon dioxide levels, there were only 4 minutes in which the larger values at ground level each proved significant (minutes 2,3,4, and 5; $p < .02$) and, for the mouth-and-nose area, only during minute 8 was the difference in carbon dioxide level at ground level statistically greater than at 8,000 feet ($p < .05$). In addition, although the mouth-and-nose levels in PBE #2 often exceeded 4% near the end of the test period at both ground level and 8,000 feet, the mean 15-minute values never surpassed 4%. The 5% value, although obtained, was never exceeded for 2 minutes by any subject.

Internal Temperature:

Requirement 5 of Action Notice A-8150.2 states: "The internal temperature of the device shall not exceed 40°C, at an ambient temperature of 21°C. Only dry bulb temperatures were used here.

PBE #1:

Dry bulb temperatures inside PBE #1 never exceeded 40°C at either altitude. Thus, wet bulb measurements were theoretically unnecessary. In addition, there were no significant differences between the internal temperatures of PBE #1 at ground level and at 8,000 feet altitude. The mean temperatures for the 15-minute test period are shown in figure 9.

PBE #2:

Like PBE #1, there were no statistically significant internal temperature differences between ground level and 8,000 feet for PBE #2 (figure 10). Although the mean temperatures surpassed 40°C at both ground level and altitude during the latter minutes of testing, recall that these measurements reflect dry bulb temperatures only. Recall also that the wet bulb equivalents should be much lower than those recorded, and even though PBE #2 has no water vapor absorption mechanism, the temperatures recorded were too low to approach the wet bulb limit.

Inhalation/Exhalation Pressures: Action Notice A-8150.2, requirement 8 specifies: "Breathing resistance shall not exceed 3.5 inches of water from sea level to 8,000 feet altitude."

PBE #1:

None of the subjects using PBE #1 surpassed this limit, and the mean differences between inhalation pressures at ground level and 8,000 feet altitude were also insignificant. However, exhalation

HOOD CO₂ VALUES

PBE # 1
GROUND LEVEL VS 8000 FEET

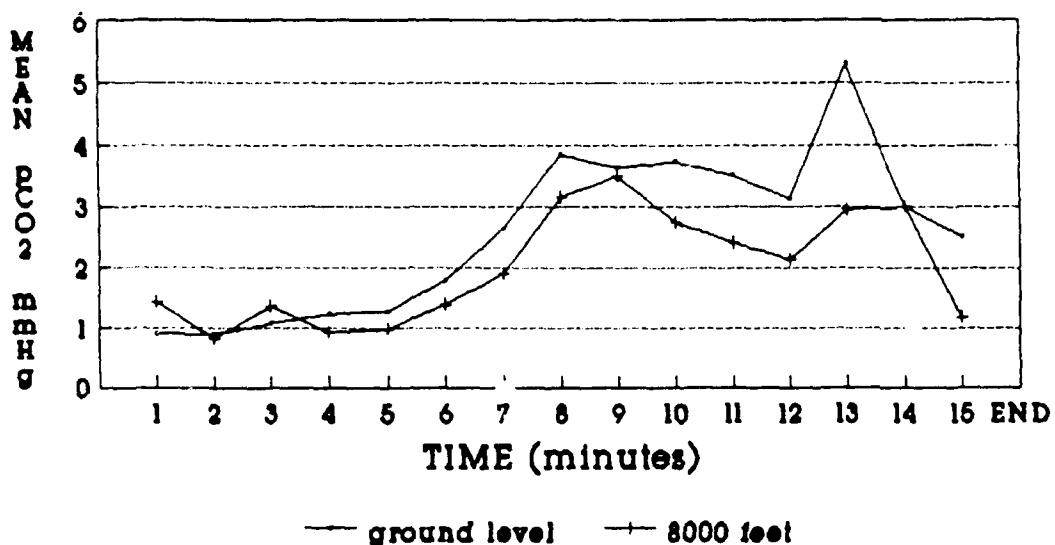


FIGURE 5

ORAL-NASAL CO₂ VALUES

PBE # 1
GROUND LEVEL VS 8000 FEET

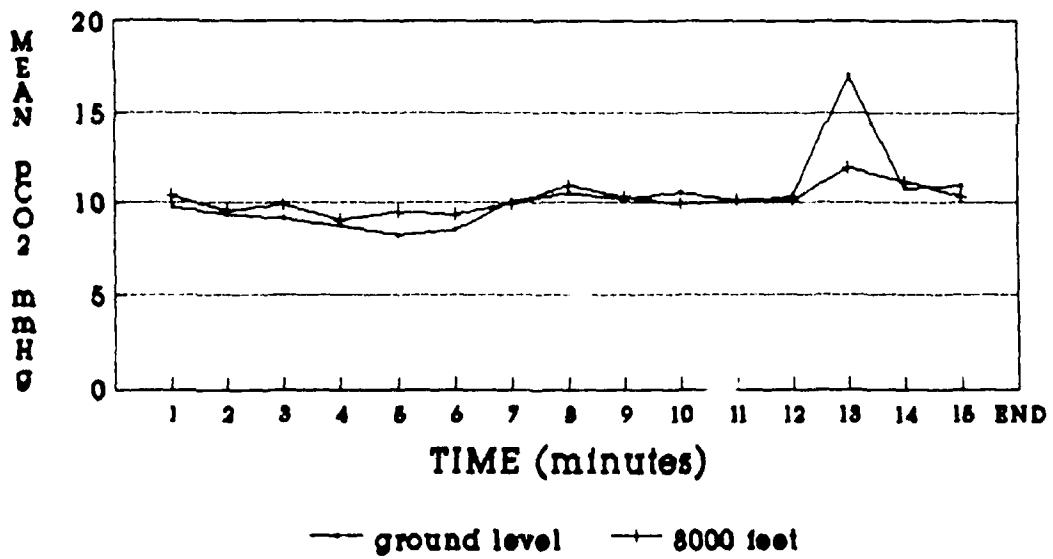


FIGURE 6

HOOD CO₂ VALUES

PBE # 2
GROUND LEVEL VS 8000 FEET

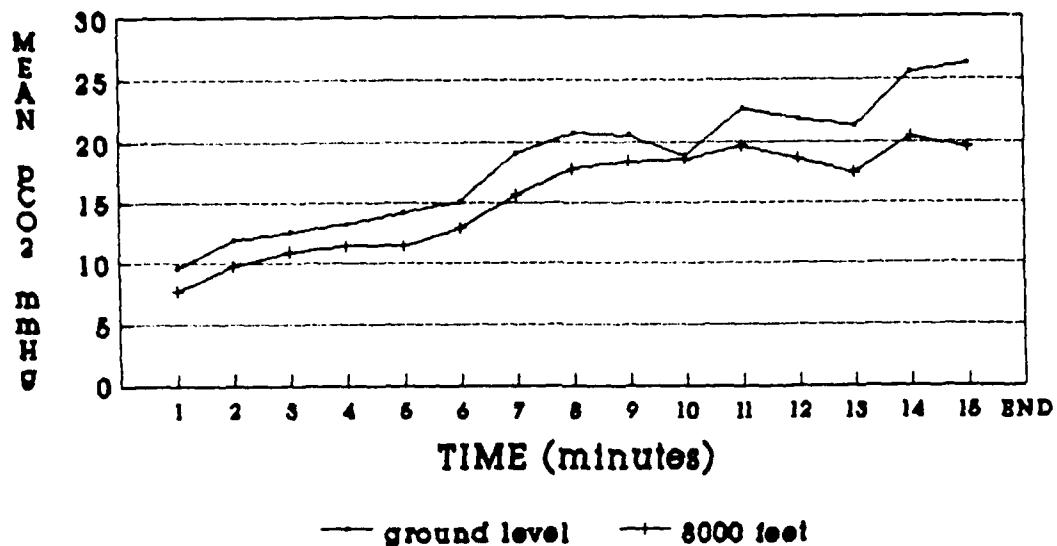


FIGURE 7

MOUTH-NOSE CO₂ VALUES

PBE # 2
GROUND LEVEL VS 8000 FEET

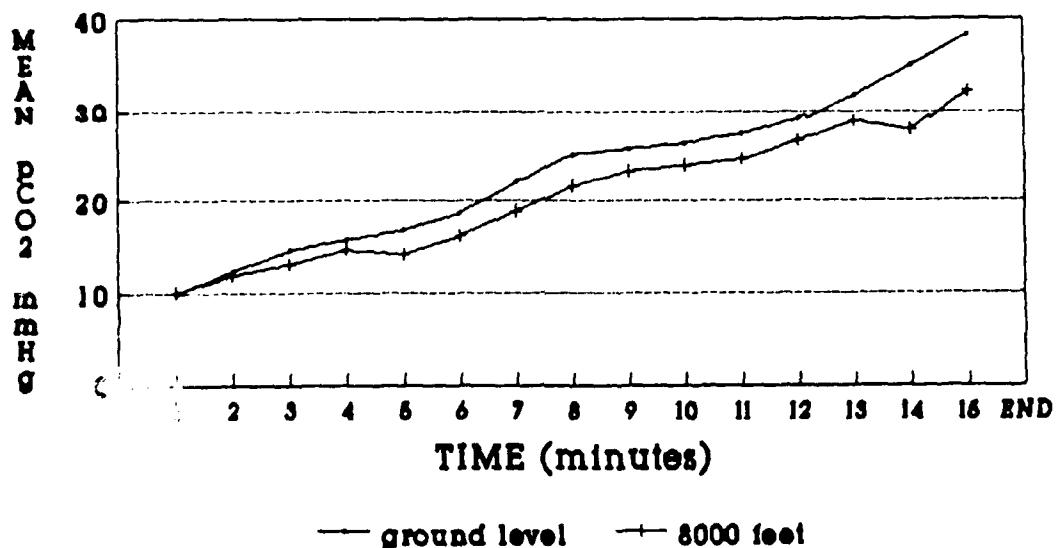


FIGURE 8

pressures at ground level exceeded those at 8,000 feet at all times, reaching statistical significance during minutes 11, 12, 14, and 15 ($p < .03$; figure 11). This effect was probably caused by the increased ambient atmospheric pressure at ground level, and thus, significant pressure differences at minute 13, which would also have occurred within this time period, were probably masked by the alphabet recitation requirement. The failure to find large differences during the early minutes of the test period was probably due to the initial influx of oxygen produced by the chlorate candle when the hood was activated. This influx caused the hood to "balloon," which increased the internal pressure and, thus, the exhalation resistance (at both altitudes) until the workload-induced respiration requirements had compensated for this initial burst of oxygen, leaving the ambient atmospheric pressure to control exhalation resistance.

PBE #2:

None of the PBE #2 subjects exceeded the breathing resistance limit. However, unlike PBE #1, there were no significant mean differences between inhalation pressures at ground level and at 8,000 feet altitude because, while the early exhalation pressures at ground level tended to exceed those at 8,000 feet altitude, the latter values displayed a much larger variance (figure 12). These effects again appeared to be dependent on the initial abundance of gas within the hood that caused it to balloon when first activated, followed by a deflation of the hood as the internal volume subsided. This process coupled with differences in the size of the dead space within the hood caused by the variation of subject head sizes, created a variable volume of air within the hood and, thus, a variable breathing resistance/pressure. This problem was not evident for PBE #1 since it contained the closed loop, oral-nasal mask system.

SUMMARY-AND-CONCLUSIONS

In summary, there was little difference in performance observed of either type of PBE at ground level and 8,000 feet altitude. Statistically significant differences were found for the following: (1) in both PBE's, oral-nasal and hood oxygen levels were significantly higher at ground level throughout testing, (2) ground level carbon dioxide levels in PBE #2 were also significantly higher than those at 8,000 feet. These increases were more pronounced in the upper hood during the early test period, and in the mouth-and-nose area only during minute 8, (3) significantly increased exhalation pressures were obtained in PBE #1 at ground level, particularly later in the test period.

The results from this investigation reveal few differences between the performance of both PBE's at 8,000 feet altitude relative to ground level. The only significant difference found was a relatively higher partial pressure of oxygen at ground level, where the absolute availability of oxygen in the ambient air is greater. Despite statistical significance, this difference had little

INTERNAL TEMPERATURE

PBE # 1
GROUND LEVEL VS 8000 FEET

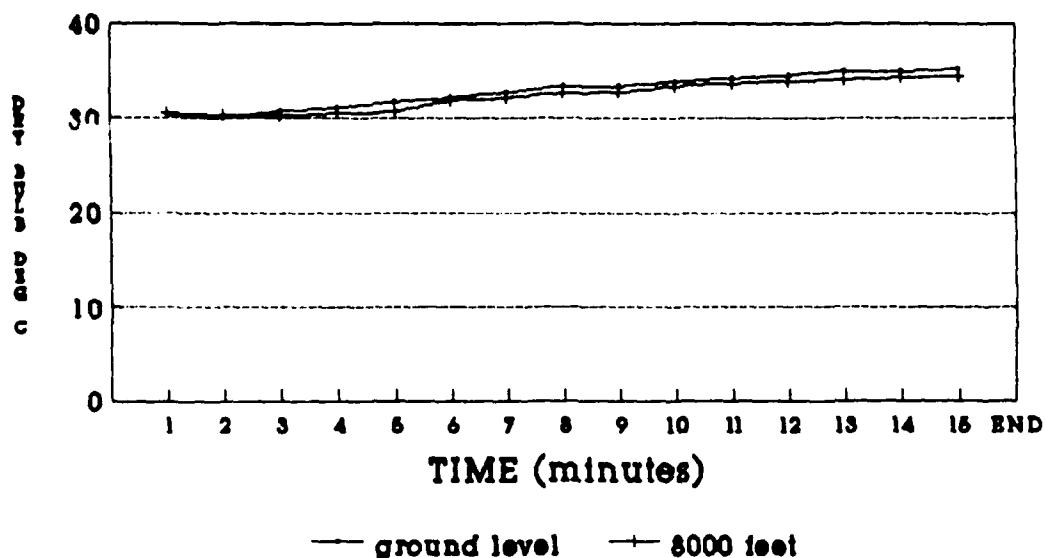


FIGURE 9

INTERNAL TEMPERATURE

PBE # 2
GROUND LEVEL VS 8000 FEET

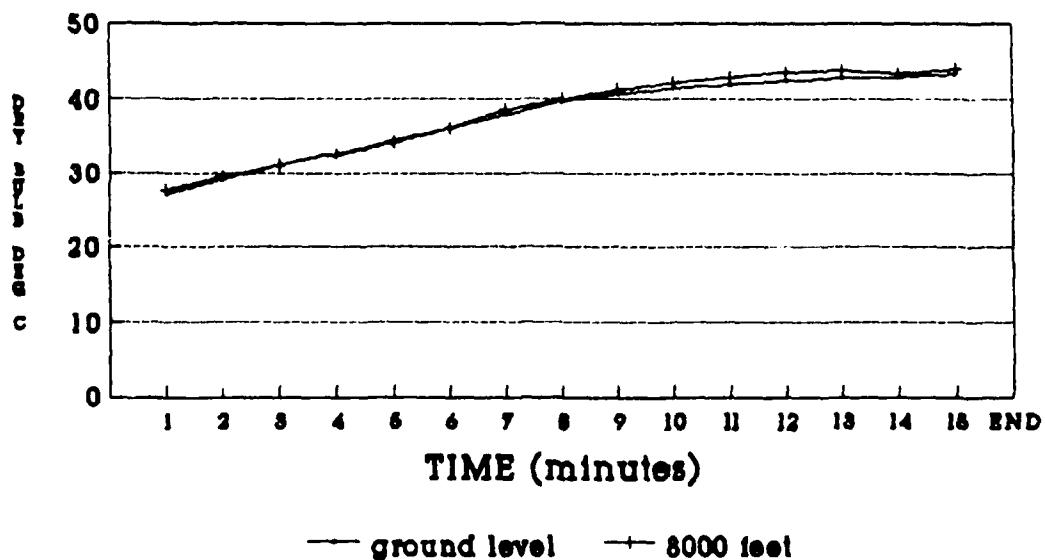


FIGURE 10

BREATHING RESISTANCE

PBE # 1
GROUND LEVEL VS 8000 FEET

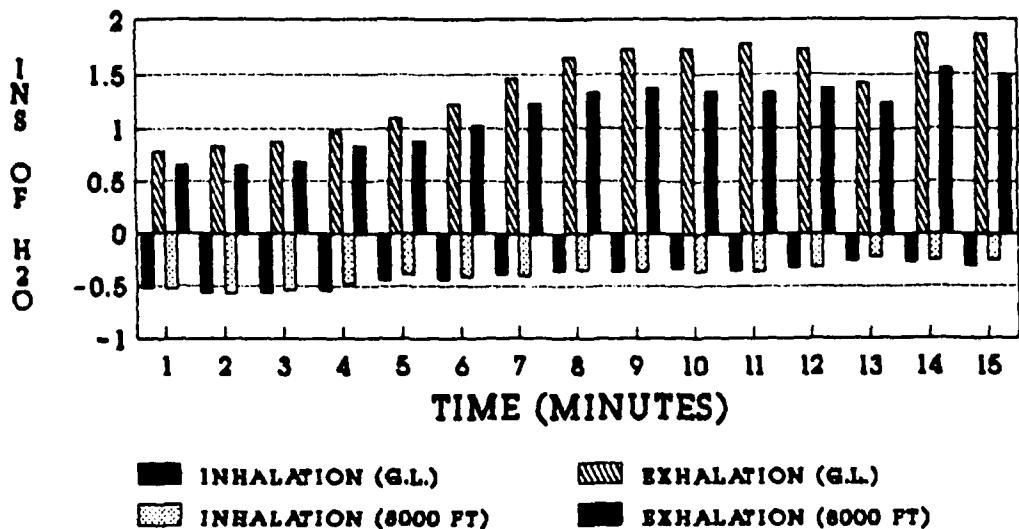


FIGURE 11

BREATHING RESISTANCE

PBE # 2
GROUND LEVEL VS 8000 FEET

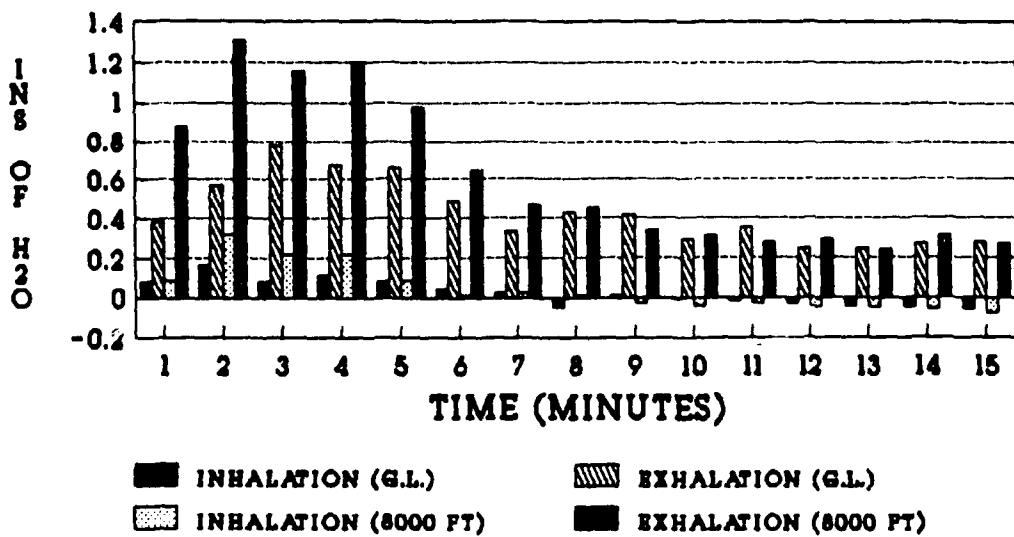


FIGURE 12

practical importance because altitude oxygen pressures were well above the 21% sea level ambient oxygen (i.e., $0.21 \times 760 \text{ mm Hg} = 159.6 \text{ mm Hg}$) and always in excess of need. This finding of decreased oxygen pressures in both types of PBE at 8,000 feet supports the requirement for testing oxygen levels in PBE at this altitude, as well as at ground level. Also, it indicates that testing at higher altitudes would be necessary if, for example, PBE certification were requested for flights at high altitudes or if the intended function of the PBE were expanded.

The changes in carbon dioxide levels appeared significant only for PBE types in which the carbon dioxide is absorbed, rather than converted to oxygen or vented to the outside. Again, however, the carbon dioxide limits specified in the Action Notice were never actually exceeded, and the concentration of carbon dioxide at 8,000 feet was relatively lower than at ground level. It would appear, therefore, that testing of carbon dioxide levels at ground level is more important than at 8,000 feet altitude, and that increasing the altitude further should cause no additional problems with carbon dioxide concentrations.

The failure to find significant internal temperature differences between ground level and 8,000 feet altitude for both types of PBE was expected. The ability of the PBE with the oral-nasal mask to shunt the exhaled air out of the hood and thereby produce lower internal temperatures was also expected, even though the chemical oxygen generator produced some additional heat. An added benefit of this shunting design was the reduction of water vapor concentration, which helped to reduce fogging.

The results for breathing resistance/pressure at ground level and 8,000 feet altitude, while statistically insignificant, revealed that the design of the PBE is critical in determining the breathing resistance/pressure performance profile. As long as there is a sufficient amount of air within either type of PBE, the breathing resistance/pressure should remain as predicted. However, the ambient atmospheric pressure will ultimately determine this function. Because ambient atmospheric pressure is always greater at lower altitudes, there would seem to be little reason for concern that exhalation pressures, which are within limits at sea level, would become aberrant at higher altitudes. However, an increase in altitude due to sudden decompression could significantly decrease the ambient atmospheric pressure and cause the internal hood atmosphere to rarify through hood ballooning, thereby causing a significant reduction in inhaled air...similar to that caused by an increase in inhalation resistance. The altitude at which such a phenomenon would occur for any particular PBE hood is unknown. That determination would probably be significant only with an expanded role for PBE.

In conclusion, both types of PBE performed adequately at both ground level and 8,000 feet. None of the parameters tested revealed significant performance decrements when the altitude was raised. However, the decrease in oxygen partial pressures,

combined with the possibility of internally rarified PBE atmosphere upon sudden decompression, reveals performance limits which could become significant given the proper circumstance. Future research into these limits, especially at higher altitudes, would be warranted if certification of PBE is requested for extremely high altitude flight or if the intended purpose of PBE is to be expanded.

REFERENCE

Guidance for Approval of Crewmember Protective Breathing Equipment.
FAA Action Notice A-8150.2, September 1, 1987.